Cambridge University Press & Assessment
978-0-521-89513-2 — Cooperative Communications and Networking
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Excerpt
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1 Introduction

Wireless communications have seen a remarkably fast technological evolution. Although separated by only a few years, each new generation of wireless devices has brought significant improvements in terms of link communication speed, device size, battery life, applications, etc. In recent years the technological evolution has reached a point where researchers have begun to develop wireless network architectures that depart from the traditional idea of communicating on an individual point-to-point basis with a central controlling base station. Such is the case with ad-hoc and wireless sensor networks, where the traditional hierarchy of a network has been relaxed to allow any node to help forward information from other nodes, thus establishing communication paths that involve multiple wireless hops. One of the most appealing ideas within these new research paths is the implicit recognition that, contrary to being a point-to-point link, the wireless channel is broadcast by nature. This implies that any wireless transmission from an end-user, rather than being considered as interference, can be received and processed at other nodes for a performance gain. This recognition facilitates the development of new concepts on distributed communications and networking via cooperation.

The technological progress seen with wireless communications follows that of many underlying technologies such as integrated circuits, energy storage, antennas, etc. Digital signal processing is one of these underlying technologies contributing to the progress of wireless communications. Perhaps one of the most important contributions to the progress in recent years has been the advent of MIMO (multiple-input multiple-output) technologies. In a very general way, MIMO technologies improve the received signal quality and increase the data communication speed by using digital signal processing techniques to shape and combine the transmitted signals from multiple wireless paths created by the use of multiple receive and transmit antennas.

Cooperative communications is a new paradigm that draws from the ideas of using the broadcast nature of the wireless channel to make communicating nodes help each other, of implementing the communication process in a distribution fashion and of gaining the same advantages as those found in MIMO systems. The end result is a set of new tools that improve communication capacity, speed, and performance; reduce battery consumption and extend network lifetime; increase the throughput and stability region for multiple access schemes; expand the transmission coverage area; and provide cooperation tradeoff beyond source–channel coding for multimedia communications.

In this chapter we begin with the study of basic communication systems and concepts that are highly related to user cooperation, by reviewing a number of concepts that will be useful throughout this book. The chapter starts with a brief description of the relevant characteristics of wireless channels. It then follows by discussing orthogonal frequency division multiplexing followed by the different concepts of channel capacity. After this, we describe the basic ideas and concepts of MIMO systems. The chapter concludes by describing the new paradigm of user cooperative communications.

1.1 Wireless channels

Communication through a wireless channel is a challenging task because the medium introduces much impairment to the signal. Wireless transmitted signals are affected by effects such as noise, attenuation, distortion and interference. It is then useful to briefly summarize the main impairments that affect the signals.

1.1.1 Additive white Gaussian noise

Some impairments are additive in nature, meaning that they affect the transmitted signal by adding noise. Additive white Gaussian noise (AWGN) and interference of different nature and origin are good examples of additive impairments. The additive white Gaussian channel is perhaps the simplest of all channels to model. The relation between the output $y(t)$ and the input $x(t)$ signal is given by

$$y(t) = x(t)/\sqrt{\Gamma} + n(t), \tag{1.1}$$

where Γ is the loss in power of the transmitted signal $x(t)$ and $n(t)$ is noise. The additive noise $n(t)$ is a random process with each realization modeled as a random variable with a Gaussian distribution. This noise term is generally used to model background noise in the channel as well as noise introduced at the receiver front end. Also, the additive Gaussian term is frequently used to model some types of inter-user interference although, in general, these processes do not strictly follow a Gaussian distribution.

1.1.2 Large-scale propagation effects

The *path loss* is an important effect that contributes to signal impairment by reducing its power. The path loss is the attenuation suffered by a signal as it propagates from the transmitter to the receiver. The path loss is measured as the value in decibels (dB) of the ratio between the transmitted and received signal power. The value of the path loss is highly dependent on many factors related to the entire transmission setup. In general, the path loss is characterized by a function of the form

$$\Gamma_{\mathrm{dB}} = 10\nu \log(d/d_0) + c, \tag{1.2}$$

where Γ_{dB} is the path loss Γ measured in dB, d is the distance between transmitter and receiver, ν is the path exponent, c is a constant, and d_0 is the distance to a power measurement reference point (sometimes embedded within the constant c). In many practical scenarios this expression is not an exact characterization of the path loss, but is still used as a sufficiently good and simple approximation. The path loss exponent ν characterizes the rate of decay of the signal power with the distance, taking values in the range of 2 (corresponding to signal propagation in free space) to 6. Typical values for the path loss exponent are 4 for an urban macro cell environment and 3 for urban micro cell. The constant c includes parameter related to the physical setup of the transmission such as signal wavelength, antennas height, etc.

Equation (1.2) shows the relation between the path loss and the distance between the transmit and the receive antenna. In practice, the path losses of two receive antennas situated at the same distance from the transmit antenna are not the same. This is, in part, because the transmitted signal is obstructed by different objects as it travels to the receive antennas. Consequently, this type of impairment has been named *shadow loss* or *shadow fading*. Since the nature and location of the obstructions causing shadow loss cannot be known in advance, the path loss introduced by this effect is a random variable. Denoting by S the value of the shadow loss, this effect can be added to (1.2) by writing

$$\Gamma_{\text{dB}} = 10\nu \log(d/d_0) + S + c. \tag{1.3}$$

It has been found through experimental measurements that S when measured in dB can be characterized as a zero-mean Gaussian distributed random variable with standard deviation σ (also measured in dB). Because of this, the shadow loss value is a random value that follows a log-normal distribution and its effect is frequently referred as *log-normal fading*.

1.1.3 Small-scale propagation effects

From the explanation of path loss and shadow fading it should be clear that the reason why they are classified as large-scale propagation effects is because their effects are noticeable over relatively long distances. There are other effects that are noticeable at distances in the order of the signal wavelength; thus being classified as small-scale propagation effects. We now review the main concepts associated with these propagation effects.

In wireless communications, a single transmitted signal encounters random reflectors, scatterers, and attenuators during propagation, resulting in multiple copies of the signal arriving at the receiver after each has traveled through different paths. Such a channel where a transmitted signal arrives at the receiver with multiple copies is known as a multipath channel. Several factors influence the behavior of a multipath channel. One is the already mentioned random presence of reflectors, scatterers and attenuators. In addition, the speed of the mobile terminal, the speed of surrounding objects and the transmission bandwidth of the signal are other factors determining the behavior of the channel. Furthermore, due to the presence of motion at the transmitter, receiver, or surrounding objects, the multipath channel changes over time. The multiple copies of the transmitted signal, each having a different amplitude, phase, and delay, are added at the receiver creating either constructive or destructive interference with each other. This results in a received signal whose shape changes over time. Therefore, if we denote the transmitted signal by $x(t)$ and the received signal by $y(t)$, we can write their relation as

$$y(t) = \sum_{i=1}^{L} h_i(t)x(t - \tau_i(t)), \tag{1.4}$$

where $h_i(t)$ is the attenuation of the i-th path at time t, $\tau_i(t)$ is the corresponding path delay, and L is the number of resolvable paths at the receiver. This relation implicitly assumes that the channel is linear, for which $y(t)$ is equal to the convolution of $x(t)$ and the channel response at time t to an impulse sent at time τ, $h(t, \tau)$. From (1.4), this impulse response can be written as

$$h(t, \tau) = \sum_{i=1}^{L} h_i(t)\delta(t - \tau_i(t)), \tag{1.5}$$

Furthermore, if it is safe to assume that the channel does not change over time, the received signal can be simplified as

$$y(t) = \sum_{i=1}^{L} h_i x(t - \tau_i),$$

and the channel impulse response as

$$h(t) = \sum_{i=1}^{L} h_i \delta(t - \tau_i). \tag{1.6}$$

In many situations it is convenient to consider the discrete-time baseband-equivalent model of the channel, for which the input–output relation derived from (1.4) for sample m can be written as

$$y[m] = \sum_{k=l}^{L} h_k[m]x[m - k], \tag{1.7}$$

where $h_k[m]$ represents the channel coefficients. In this relation it is implicit that there is a sampling operation at the receiver and that all signals are considered as in the baseband equivalent model. The conversion to a discrete-time model combines all the paths with arrival time within one sampling period into a single channel response coefficient $h_l[m]$. Also, note that the model in (1.7) is nothing more than a time-varying FIR digital filter. In fact, it is quite common to call the channel model based on the impulse response as the tapped-delay model. Since the nature of each path, its length, and the presence of reflectors, scatterers, and attenuators are all random, the channel coefficients h_k of a time-invariant channel are random variables (and note that the redundant time index needs not be specified). If, in addition, the channel changes randomly over time, then the channel coefficients $h_k[m]$ are random processes. Such an effect needs to be taken into consideration with functions that depend on the coefficients, since now they become random functions.

1.1.4 Power delay profile

The function determined by the average power associated with each path is called the *power delay profile* of the multipath channel. Figure 1.1 shows the power delay profile for a typical wireless channel slightly modified from the ITU reference channel model called "Vehicular B" [87]. Several parameters are derived from the power delay profile or its spectral response (Fourier transform of the power delay profile), which are used to both characterize and classify different multipath channels:

- The *channel delay spread* is the time difference between the arrival of the first measured path and the last. If the duration of the symbols used for signaling over the channel exceeds the delay spread, then the symbols will suffer from inter-symbol interference. Note that, in principle, there may be several signals arriving through very attenuated paths, which may not be measured due to sensitivity of the receiver. This makes the concept of delay spread tied to the sensitivity of the receiver.
- The *coherence bandwidth* is the range of frequencies over which the amplitude of two spectral components of the channel response are correlated. The coherence bandwidth provides a measurement of the range of frequencies over which the channel shows a flat frequency response, in the sense that all the spectral components have approximately the same amplitude and a linear change of phase. This means that if the transmitted signal bandwidth is less than the channel coherence bandwidth, then all the spectral components of the signal will be affected by the same attenuation and by a linear change of phase. In this case, the channel is said to be a *flat fading channel*. In another way, since the signal sees a channel with flat frequency response, the channel is often called a *narrowband channel*. If on the contrary, the transmitted signal

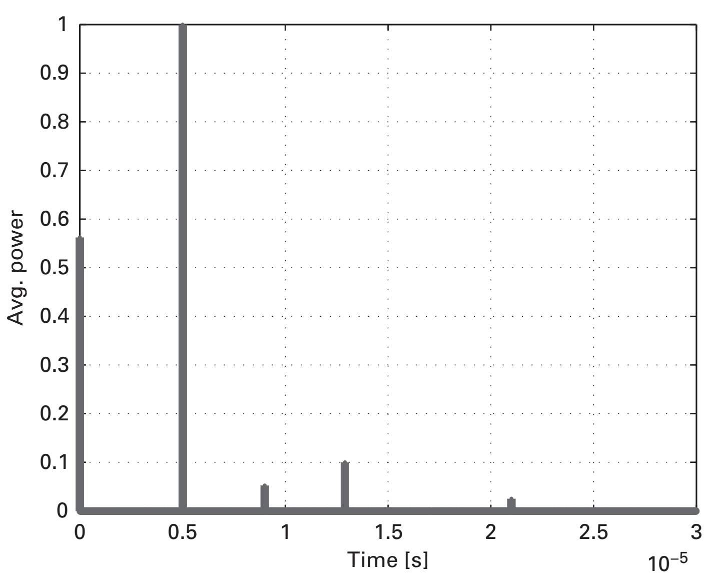

Fig. 1.1 The power delay profile of a typical wireless channel.

bandwidth is more than the channel coherence bandwidth, then the spectral components of the signal will be affected by different attenuations. In this case, the channel is said to be a *frequency selective channel* or a *broadband channel*.

Example 1.1 There are a large number of different channel models that have been used over time for evaluation of communications systems. The large number is due to the different settings found in the plethora of communication systems already in the market or under development. In Tables 1.1 through 1.4 we summarize the parameters of the power delay profile for some of the channels defined in the ITU recommendation M.1225, which is intended for a system operating at a carrier frequency of 2 GHz. In the ITU recommendation, several channel models are discussed so as to account for typically large variability of wireless channels. In this example, Tables 1.1 and 1.2 show the parameters for channels corresponding to a pedestrian setting. As its names indicates, this environment is designed to model pedestrian users, either outside on a street or inside a residence, with small cells, low transmit power and outside base stations with low antenna heights. Tables 1.3 and 1.4 show the parameters for channels corresponding to a vehicular setting. In contrast with the pedestrian environment, the vehicular case models larger cell sizes and transmit power. Also to account for the large variability of wireless channels, two types of channel models are specified for both the pedestrian and vehicular cases. The two types of channels are called "type A" and "type B", where the channel type A is defined as that of a low delay spread case that occurs frequently and channel type B is defined as that of the median delay spread case.

Table 1.1 ITU-R M.1225 Pedestrian A channel parameters.

Tap	Relative delay [ns]	Average power [dB]
1	0	0
2	110	−9.7
3	190	−19.2
4	410	−22.8

Table 1.2 ITU-R M.1225 Pedestrian B channel parameters.

Tap	Relative delay [ns]	Average power [dB]
1	0	0
2	200	−0.9
3	800	−4.9
4	1200	−8.0
4	2300	−7.8
4	3700	−23.9

Table 1.3 ITU-R M.1225 Vehicular A channel parameters.

Tap	Relative delay [ns]	Average power [dB]
1	0	0
2	310	−1.0
3	710	−9.0
4	1090	−10.0
4	1730	−15.0
4	2510	−20.0

Table 1.4 ITU-R M.1225 Vehicular B channel parameters.

Tap	Relative delay [ns]	Average power [dB]
1	0	−2.5
2	300	0
3	8900	−12.8
4	12900	−10.0
4	17100	−25.2
4	20000	−16.0

Figures 1.2 and 1.3 show in the time and frequency domain, respectively, the impulse response in Tables 1.1 through 1.4. The figures illustrate the typical variability of channel models, both in terms of delay spread and coherence bandwidth. Also note how, within the same type A or type B channels, the vehicular channels exhibit a larger delay spread. ▲

Whether a particular channel will appear as flat fading or frequency selective depends, of course, on the channel delay spread, but it also depends on the characteristics of the signal being sent through the channel. Figure 1.4 shows a section of the spectral response of the channel with power delay profile shown in Figure 1.1. We can see that if the transmitted signal has a bandwidth larger than a few tens of kilohertz, then the channel will affect differently those spectral components of the transmitted signal that are sufficiently apart.

This can be seen in Figure 1.5, which shows the time and frequency domain input and output signals to the channel in Figures 1.1 and 1.2. In Figure 1.5, the input signal is a raised cosine pulse with roll off factor 0.25 and symbol period 0.05 μs. For this pulse, the bandwidth is approximately 2 MHz. This makes the channel behave like a frequency selective channel. As can be seen in the frequency domain representation of the output pulse in Figure 1.5, the typical result of the frequency selectivity is that there are large differences in how each spatial component is affected. In the time domain, it can be

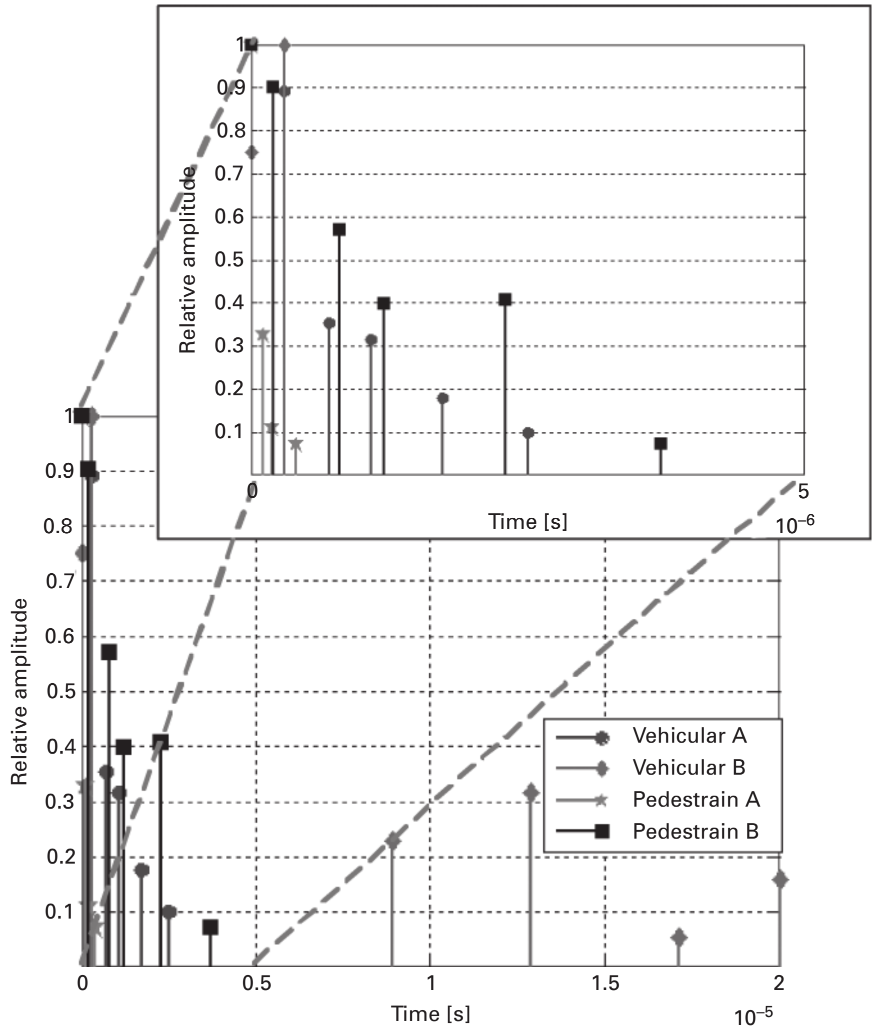

Fig. 1.2 The amplitude of the different paths for the channels in Tables 1.1 through 1.4. The amplitudes of each path are shown relative to the value of the path with larger gain.

seen that the single pulse at the input of the channel appears repeated at the output with different delays corresponding to each path.

Such a phenomenon can also be seen in detail in Figure 1.6, which shows the output pulse and each of the pulses arriving through a different path, with their corresponding delay. Since the delay associated with some path is larger than the symbol period, the multipath, frequency selective channel is suffering from intersymbol interference (ISI). The fact that a time domain phenomenon such as instances of a signal arriving with different delays, translate into a frequency domain effect, such as frequency selectivity, can be understood in the following way. When the signals with different delays from the multipath get superimposed at the receive antenna, the different delay translates

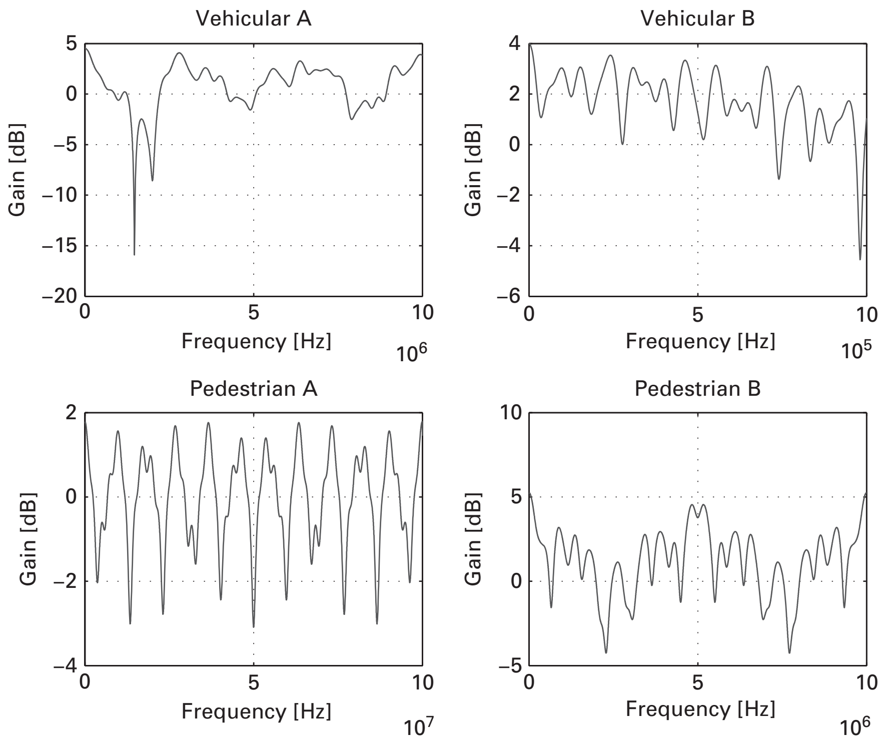

Fig. 1.3 Spectral response of the channels with power delay profile in Tables 1.1 through 1.4.

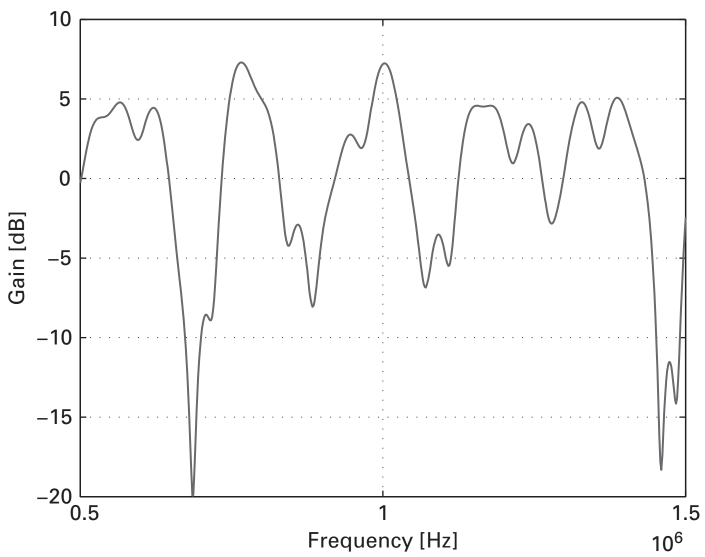

Fig. 1.4 Section of the spectral response of the channel with power delay profile shown in Figure 1.1.

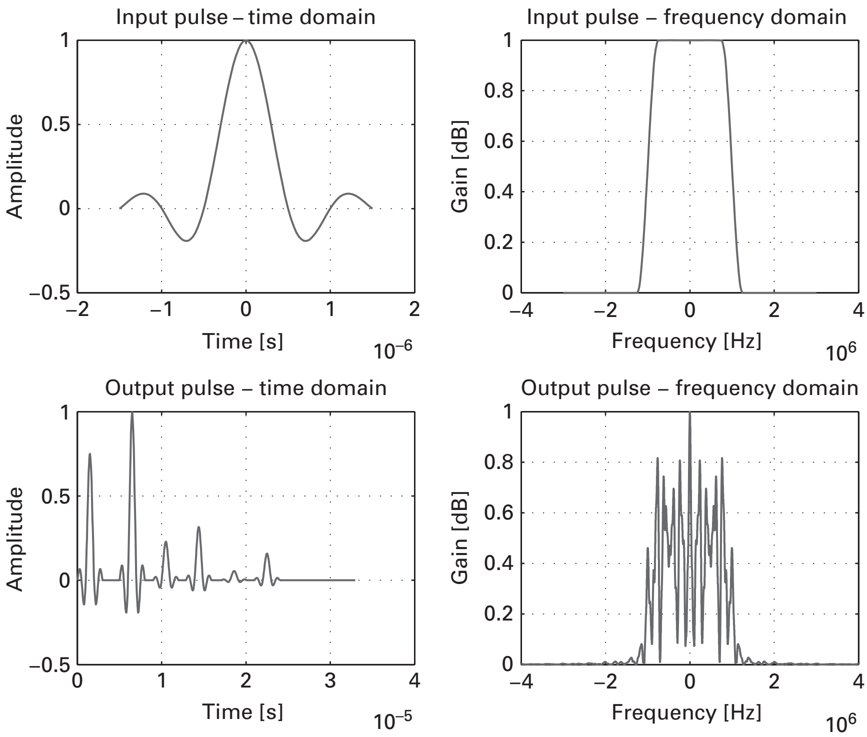

Fig. 1.5 The input and output pulses to a frequency selective channel.

into different phases. Depending on the phase difference between the spectral components, their superposition may result into destructive or constructive interference. Even more, because the relation between phase and path delay for each spectral component of the arriving signal varies with the frequency of the spectral component, the signal will undergo destructive or constructive interference of different magnitude for each spectral component, resulting in the frequency response of the channel not appearing of constant amplitude.

Figures 1.7 and 1.8 show the time and frequency domains input and output signals to the channel in Figures 1.1 and 1.4 when the input pulse have a transmission period long enough that the channel behaves as non frequency selective. In this case, the input pulse has a bandwidth of approximately 2 KHz, for which the frequency response of the channel appears roughly flat. Consequently, the transmitted pulse suffers little alterations in both time and frequency domains. Also, note that now with the longer duration of the pulse, the delays associated with different channel paths can be practically neglected and there is no ISI.

In addition to power delay profile and channel delay spread, there are other parameters related to time-varying characteristics of the wireless channel. As we have said, the motions of the transmitter, the receiver or the reflectors along the signal propagation path creates a change of the channel transfer characteristics over time. Such motions also introduce frequency shifts due to the Doppler shift effect. To characterize the channel in